# Should China subsidise cofiring to meet its 2020 bioenergy target? A spatio-techno-economic analysis

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Title Page

**Should China subsidise cofiring to meet its 2020 bioenergy target?**
**A spatio-techno-economic analysis**

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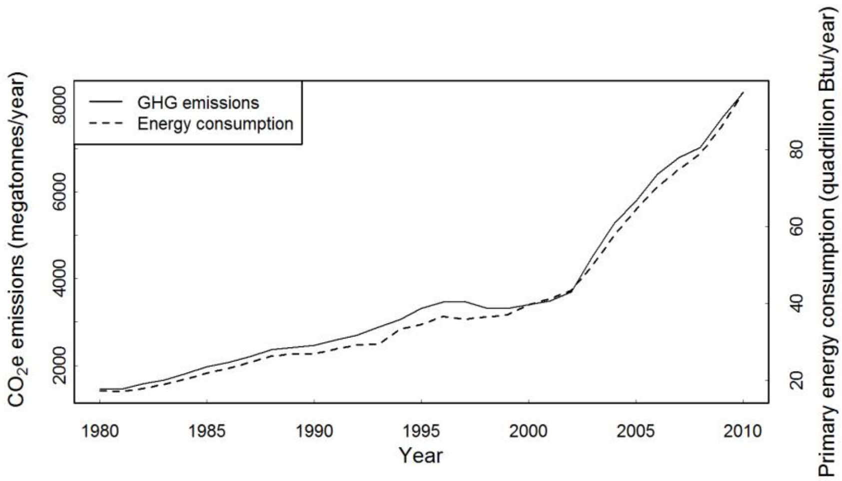
**Abstract**

China has developed ambitious bioenergy installation targets as part of its broader goals to increase its renewable energy generating capacity and decarbonise its economy. At present its main financial incentive to support bioenergy projects is a feed-in-tariff provided to units that generate electricity with 80% or more of their feedstock energy coming from agricultural residue biomass. Although this policy has catalysed the construction of many bioenergy units, there are reports that these projects are experiencing serious financial and technical problems, leading to low operational efficiency and even closure. An alternative option for China's agricultural residues is cofiring with coal in existing power stations. However this is currently unprofitable for power station operators, as cofiring is not eligible for financial assistance through the bioenergy feed-in-tariff. In light of China's ambitious target to install 30GW of bioenergy generation capacity by 2020, this paper investigates the extent to which extension of the bioenergy feed-in-tariff to include cofiring could contribute towards this goal. The results suggest that there is significant co-location of China's coal-fired powerstations and agricultural residues, with 39% of China's straw energy resources located within 50km of a power station. Assuming cofiring ratios of up to 10% coal energy replacement, the analysis finds that an annual 89-116TWh of electricity could be generated by cofiring agricultural residues collected within 50km radii of powerstations. If China extends its bioenergy subsidies to include cofiring, we estimate that an annual 72-100TWh can be produced at an internal rate of return of 8% or more. This equates to 48-67% of the bioenergy generation that China might expect if it were to meet its target of installing 30GW of bioenergy capacity. Overall this indicates a strong case for the Chinese government to extend its existing bioenergy feed-in-tariff to include cofiring at low energy replacement ratios.

## Introduction

Over the past 30 years, China has displayed an unprecedented average annual GDP growth rate of 9% (NBSC, 2012). During this time the nation's primary energy consumption and annual $CO_2$e emissions have both increased by over 550%, showing a close correlation (Figure 1; (EIA, 2015; World Bank, 2015)) . In light of the evidence that energy consumption and greenhouse gas (GHG) emissions have been causally linked up to this point (Fei *et al.*, 2011; Wang *et al.*, 2011a; Li & Leung, 2012), China is now taking substantial steps to 'de-couple' its energy use from $CO_2$e emissions, driven predominantly by environmental and climate change concerns (Li & Wang, 2012).

*Figure 1: Graph of China's annual $CO_2$e emissions and primary energy consumption from 1980-2010*




### *Renewable energy development in China*

Decarbonisation of the energy sector is a central priority within the de-coupling goal, particularly because China's energy generation sector is dominated by coal-fired power stations, which produce 70% of the gross national energy supply (Li & Leung, 2012; Yuan *et* *al.*, 2014). Recognising this reliance on coal and the associated environmental implications, China has developed a variety of growth and emission trajectory targets, the latest of which is that the carbon intensity of the economy must be reduced by 40-45% of 2005 levels by 2020 (Yuan *et al.*, 2014), with related targets for the share of non-fossil fuel energy to increase to 11.4% and 15% of the total energy supply, by 2015 and 2020, respectively *(ibid).* As part of this target, the State Council issued a plan in 2014 to cap coal consumption at 4.2Gt by 2020, and to reduce its share within the energy mix to 62% (Cornot-Gandolphe, 2014).

There has been substantial progress in meeting these renewable energy targets. By 2010 China had installed 216GW of hydro-power, 31GW wind power, 5.5GW biomass power and 0.8GW solar power, representing 113%, 620%, 100% and 160% of the original 2010 targets for each technology, respectively (Yuan *et al.*, 2014). However, despite having met the 2010 target for biomass energy installation, concern is growing over China's ability to meet the 2020 target of 30GW installed biomass power capacity. Meeting this target would produce an estimated annual 148.8TWh of bioenergy (Xingang *et al.*, 2013), which is equivalent to 3.1% of China's 2012 total net electricity generation of 4768TWh (EIA, 2015). Despite investing over $10 billion in biomass energy development between 2006 and 2011(Xingang *et al.*, 2013), reports suggest that China's second largest biopower plant operator has not started construction on any biomass projects during 2012-2014, despite reporting a gross profit of $14.8m for its biomass projects in 2011, and having submitted plans for a further 26 biomass power plants (Gosens, 2015).

Various reasons have been cited for the slow down in construction of biomass power plants, including high feedstock prices, poor coordination between projects and technical operating difficulties (Han *et al.*, 2008; Sang & Zhu, 2011; Zhao & Yan, 2012; Xingang *et al.*, 2013; Zhang *et al.*, 2013; Yuan *et al.*, 2014). Moreover, there are reports that the existing financial support available through subsidies, grants and the renewable energy feed-in-tariff may not be sufficient to meet the 8% internal rate of return (IRR) that Chinese regulations outline as expected for investments in the power sector (Gosens, 2015).

### ***Current support for bioenergy generation from crop residues***

At present, China provides various capital grants, tax breaks and a feed-in-tariff (\$0.12 kWh$^{-1}$; Zhang *et al.*, 2014a) to bioenergy projects that utilise agricultural residues to generate electricity. The targeting of agricultural residues is important, as China produces an annual 800 million tonnes (Mg) of straw, of which an estimated 505 Mt are available after retaining sufficient straw to maintain soil quality (Jiang *et al.*, 2012). However a significant proportion of this biomass resource is burned in-field as a waste, as a result of reduced demand for straw as a household fuel, a scarcity of on-farm labour for straw collection, and the imperative for increasingly time-poor farmers to quickly dispose of waste residues before planting the next crop (Wu *et al.*, 2001; Lin & Song, 2002; Yu, 2003; Cao *et al.*, 2008). Straw burning on this scale is an inefficient use of biomass resources and causes significant local air pollution, emitting high levels of particulate matter (PM), hydrocarbons and other pollutant gases to the atmosphere (Duan *et al.*, 2004; Yan *et al.*, 2006; Qu *et al.*, 2012). However, despite the Chinese government announcing a variety of straw burning bans since the late 1990s, enforcement has proven difficult, costly and ineffective (Jingjing *et al.*, 2001; Qu *et al.*, 2012).

Instead, the government has established policies that financially incentivise the use of these residues as feedstock for bioenergy generation (Clare *et al.*, 2014). However these subsidies are only available to units deriving 80% or more of their power from biomass. This restriction effectively rules out the cofiring of agricultural residues in existing coal-fired power stations, because cofiring tends only to be technically feasible when ~10% or less of the coal feedstock is offset by biomass, on an energy replacement basis (Al-Mansour & Zuwala, 2010; Tumuluru *et al.*, 2011; IEA, 2012). This reticence to support cofiring at lower energy replacement ratios stems in part from perceived difficulties in verifying the ratio of co-fired biomass at the coal fired power stations, and thus calculating the level of subsidy to award to each producer (Dong, 2012; Liu *et al.*, 2014; Gosens, 2015). However there remains significant interest in the concept of cofiring in China, with a variety of scoping projects commissioned through international partnerships (DECC, 2008; Minchener, 2008), government-funded demonstration plants in Shandong and Shaanxi provinces (Liu *et al.*, 2014) and various research studies reporting that cofiring agricultural residues in China can be both technically feasible and financially viable (Lu & Zhang, 2010; Wang *et al.*, 2011b; Liu *et al.*, 2014).

***The benefits of cofiring***

In theory cofiring should lead to a variety of positive environmental outcomes. For example, Mann & Spath, (2001) report that cofiring rates of 5% and 15% by heat input can reduce GHG emissions from a coal fired power plant by 5.4% and 18.2%, respectively. Moreover, cofiring can also reduce $SO_2$ and $NO_x$ emissions (Mann & Spath, 2001; Huang *et al.*, 2006; Basu *et al.*, 2011), which are significant contributors to acid rain.

Cofiring is also significantly more desirable than biomass-only plants from the perspective of energy conversion: the average energy conversion efficiency of a biomass-only power unit is 25% (van Loo & Koppejan, 2008), whereas coal-fired powerstations are around 36% in OECD countries (Wicks & Keay, 2005), increasing to 45% for more modern units. Moreover, directly cofiring biomass with coal at relatively low ratios (5-10% energy equivalent) requires only minor alterations to the pre-existing feed and feedstock storage facilities, whereas building new bioenergy units entails construction, land, technical expertise, staffing and administrative costs (Zhang *et al.*, 2014).

With the growth of biomass-only units in China slowing, or even reversing, under the existing subsidy scheme, this paper therefore investigates how extending China's current bioenergy subsidy scheme to include cofiring could assist in meeting the country's target to install 30GW of bioenergy generation capacity by 2020. This question is examined through spatial, technical and financial lenses, using a unique geographically-linked dataset of China's coal-fired power stations and agricultural residue distribution.

Three previously unanswered questions are addressed. First, we assess the geographic proximity of the three main agricultural residues (maize, wheat and rice straw) to China's existing coal-fired power plants, providing the first national-scale study of straw and power plant spatial co-location. Second, we combine data on power station size, efficiency and technical cofiring capacity with three straw removal scenarios, to assess the technical potential for cofiring across China. Finally, we investigate the financial case for agricultural residue cofiring from the perspective of investors. To date there has been suggestive case-study evidence that China's power stations can cofire straw profitably (Minchener, 2008; Lu & Zhang, 2010), however we provide the first national scale estimate of the number of TWh that powerstations would produce from cofiring agricultural residues if the existing bioenergy subsidy scheme was extended to include cofiring.

## Materials and Methods

### *Coal-fired power station data*

China's coal fired power stations were identified using publicly available lists for 2006-2012 published by the China Electricity Council, (2014) which provides power station names, administrative addresses and installed generating capacities (GW) of individual generation units. No power plants are located on China's islands, therefore this analysis focuses exclusively on mainland China.

The geographic coordinates of each power station were determined by searching for its administrative address online and associated instructions on how to visit the power plant by road. Google Earth software was then used to pinpoint exact geographic coordinates for the power plants, using the most recently available images[1]. Overall, 268 powerstations were located, totalling 401GW of installed power generation capacity. Based on recent estimates, China's coal-fired generation capacity will be 960GW in 2015 (Industrial Efficiency Policy Database, 2014) and thus we are able to account for 42% of this estimate. It is likely that many of the smaller powerstations on the lists could not be found due to China's recent policy of shutting power plants with low efficiency and poor environmental records (Zhang & Cheng, 2009; Chen & Xu, 2010). It is also likely that many larger, efficient (1GW+) plants have been built since the last available list was published (2012), which we were therefore not able to account for. Table 1 provides a summary of the number of power stations (n) and total installed capacity (GW) within geographical sub-regions of China. The listed regions are provinces, unless otherwise specified.

*Table 1: The number (n) of powerstations and total installed capacity (GW) of powerstations that were geographically located in each of China's sub-regions*

[1] The x-y coordinates of the power stations cannot be published for security reasons.

| Area | n | GW |
|---|---|---|
| Anhui | 16 | 21 |
| Chongqingshi[1] | 1 | 2 |
| Fujian | 7 | 16 |
| Gansu | 1 | 2 |
| Guangdong | 20 | 28 |
| Guangxi[2] | 4 | 5 |
| Guizhou | 7 | 11 |
| Hebei | 16 | 27 |
| Heilongjiang | 6 | 9 |
| Henan | 16 | 21 |
| Hubei | 9 | 12 |
| Hunan | 9 | 13 |
| Jiangsu | 32 | 46 |
| Jiangxi | 4 | 6 |
| Jilin | 3 | 4 |
| Liaoning | 7 | 11 |
| Neimenggu[2] | 15 | 27 |
| Ningxia[2] | 4 | 6 |
| Shaanxi | 11 | 15 |
| Shandong | 23 | 34 |
| Shanghai[1] | 11 | 16 |
| Shanxi | 20 | 27 |
| Sichuan | 4 | 6 |
| Tianjin[1] | 5 | 7 |
| Xinjiang[2] | 1 | 1 |
| Yunnan | 4 | 7 |
| Zhejiang | 12 | 23 |
| TOTAL | 268 | 401 |

[1] Municipality [2] Autonomous region

Expert opinion and literature (Xiong *et al.*, 2009; Chen & Xu, 2010) were used to estimate the energy conversion efficiency of each power station, based on the size of individual units that made up the largest proportion of its total installed generation capacity (see Table 2). For example, a power station made up of 2x350MW units and 1x600MW units would be assigned to the 300-600MW category, whereas one of 1x350MW units and 1x600MW unit would be assigned to the 600-1000MW category. Where the proportional contributions were even, the powerstation was assigned to the higher unit capacity group.

*Table 2: Estimated energy conversion efficiencies for power plants, based on the size of individual units that make up the largest proportion of the overall generation capacity*

| | <300MW | 300-600MW | 600-1000MW | >1000MW |
|---|---|---|---|---|
| Energy conversion efficiency (%) | 30 | 34 | 39 | 45 |
| No. of plants (n) | 10 | 92 | 160 | 6 |

### *Agricultural residue data*

County-level statistical data of grain yields was sourced from China's National Bureau of Statistics (NBS), generated from a 2006 county-level agricultural survey combined with agricultural census data (Wang *et al.*, 2013). The data focuses on maize, wheat and rice yields, which together account for ~82% of China's agricultural residue production (44%, 22% and 17% for maize, wheat and rice, respectively; Junfeng *et al.*, (2005)) and which are the most commonly used fuels in Chinese biopower plants (Gosens, 2015). We do not consider purpose-grown bioenergy crops as they are small in number, subject to strict land use limitations and geographically dispersed. In contrast, agricultural straw is plentiful, consistently produced each year, and widely distributed throughout the country.

Data on maize, wheat and rice grain production was transformed into an estimate of straw energy potential using data on residue:crop ratios, straw moisture content and straw energy content (Cuiping *et al.*, 2004; Ming *et al.*, 2008). Table 3 details the assumptions made for each straw type. These are the same parameters as those used by Wang *et al.*, (2013).

*Table 3: Assumptions in calculating available straw energy from county statistics of grain production*

| | Rice | Wheat | Maize |
|---|---|---|---|
| Residue:crop ratio | 0.68 | 0.73 | 1.25 |
| Moisture Content (%) | 15 | 15 | 15 |
| Straw energy content (MJ $kg^{-1}$) | 14.66 | 16.56 | 16.64 |

The agricultural residue data was assigned to geographical units using a farmland distribution map at 1:100,000 scale, obtained from the Resources and Environmental Sciences Data Centre (RESDC) and the Chinese Academy of Sciences. Straw energy values (MJ) were assigned to each geographic unit (1000m × 1000m pixel) based on the area of farmland contained within each pixel, assuming that all rice is allocated to wet land, and that maize and wheat are allocated equally between dry and wet land:

$$P_{i,j,t} = \left(\frac{L_{i,j,t}}{\sum L_{i,j,t}}\right) \times E_{j,t}$$

where $P$ = the energy (MJ) contained within pixel $i$, of county $j$, of land type $t$ (wet vs. dry) , $L$ = area of land contained within pixel $i$, of county $j$, of land type $t$, and $E$ = the total energy (MJ) contained within county $j$, for land type $t$.

***Sustainable rates of straw removal***

A proportion of straw residues produced each season must be ploughed back into the soil in order for straw removal to be a sustainable practice that does not harm long-term soil quality and productivity (Lal, 2004). Appropriate straw retention rates vary significantly according to soil type, weather patterns and crop growth conditions. This variation is so high that some experts suggest that there can be no accepted universal minimum standard for crop residue retention, and that field or even sub-field level decisions are most appropriate (Karlen & Johnson, 2014). We therefore constructed three straw removal rate scenarios, in order to reflect the high level of uncertainty around this model parameter,.

Straw removal scenario 1: In order to calculate the technical potential of straw to produce bioenergy through cofiring, this scenario assumes that only the stubble remaining after harvest is returned to the field, and that all other crop residues are available for bioenergy production. This mirrors the assumptions of Wang *et al.*, (2013), who use coefficients that are calculated according to whether a crop is machine or hand harvested, and the resulting height of straw stubble (expressed as a proportion of the straw total weight) that remains in the field. The harvest collection proportions for maize, wheat and rice are 0.95, 0.76 and 0.78, respectively (Ming *et al.*, 2008).

Straw removal scenario 2: In this scenario, we use the results of Jiang *et al.,* (2012) to guide our assumptions for the percentage retention of straw that is necessary to sustain soil fertility. Jiang *et al.*, (2012) calculate that 505 Mt of a possible 800 Mt of straw in China are available for bioenergy production, after accounting for sufficient straw being returned for soil conservation purposes. This suggests that 37% of straws are retained, and 63% are available. Therefore scenario 2 assumes that 63% of the total maize, wheat and rice straw produced is available for bioenergy production.

Straw removal scenario 3: This scenario uses a conservative estimate of necessary straw retention, assuming that 50% of maize, wheat and rice straw must be retained, and that the remaining 50% is available for bioenergy. This fits well with information from a variety of studies on straw removal rates in China, which suggest that straw removal should be minimised to ensure ongoing soil productivity and health (Li *et al.*, 2006; Ming *et al.*, 2008; Wang *et al.*, 2010).

### ***Competing uses of feedstocks***

Although straw residues are commonly used in China for activities such as papermaking and animal forage, it was not possible to account for the local-level demand for these activities in a national scale model. However, the data sources for straw feestock purchase prices used in the model (Zhao & Yan, 2012; Xingang *et al.*, 2013; Zhang *et al.*, 2013; Gosens, 2015) are assumed to account for the effect of such competing uses on the price of feedstocks and therefore the estimated financial viability of cofiring.

***Straw collection radii and technical cofiring ratios***

Agricultural wastes can be widely dispersed and difficult to collect, particularly within China's fragmented and small-scale farming system (Huang *et al.*, 2012). Therefore the financially viable straw collection radius will vary for each powerstation, depending on local conditions. Research literature suggests a wide range of radii are possible, from 20km (Minchener, 2008; Zhang *et al.*, 2013), or 40 to 50km (Liu & Huang, 2011; Thomas *et al.*, 2013; Liu *et al.*, 2014). Given this level of uncertainty we present technical cofiring potentials for both 20km and 50km straw collection radii. Where collection radii overlap, the straw within the overlap area is evenly distributed between the powerstations whose collection radii were overlapping. This ensures that straw is not double-counted.

There is also uncertainty regarding the cofiring ratio of biomass to coal. This depends on two key issues. The first factor is the nature and chemical composition of the biomass being cofired. For example, cofiring wood with coal can achieve higher ratios than cofiring herbaceous biomass, because the ash content of wood is lower, and thus the potential for fouling and slagging of the coal-boiler is lower (Werkelin *et al.*, 2010; IEA, 2012; Teixeira *et al.*, 2012). The second factor relates to the method of cofiring. This can either be direct (where biomass is sent through the same pulverisation process as coal and directly fired within the same boiler), indirect (where a biomass gasifier converts solid biomass into a fuel gas, which can be cleaned and then burned in the coal boiler furnace) or parallel (where a completely separate biomass boiler is installed and the steam produced is utilised in the coal power plant system; Al-Mansour & Zuwala, 2010). Direct cofiring requires the fewest modifications and thus the least additional capital investment, however it also facilitates the lowest ratio of biomass:coal cofiring compared to indirect and parallel cofiring configurations. In China, where cofiring is a nascent concept, it is most likely that direct cofiring will be used, and this is therefore the assumed technology for analysis.

### *Financial assessment of cofiring*

The internal rate of return (IRR) is calculated for individual power plants (at 2015 prices[2]) in order to determine the financial viability of cofiring to investors if China extended the current bioenergy policy to include cofiring. In order to calculate individual IRRs, the maximum cofiring rate of each powerplant was calculated according to its installed capacity (GW), energy conversion efficiency (see Table 2), annual operating time (5694 hours per year; Gosens, (2015)) and MJ of straw residues available within a 20km or 50km radius[3]. The upper limit for cofiring is assumed to be 10%, due to our assumption that direct cofiring will be the technology used, and that this means that cofiring rates must remain relatively low to avoid boilder fouling. Cofiring was also assumed to reduce powerstation efficiency by 1% (Minchener, 2008; Wang *et al.*, 2011b), the financial loss from which is included in the IRR calculation. The IRR is calculated only for the biomass cofiring element, and thus represents the additional returns that a power plant might expect when choosing to co-fire a biomass:coal ratio appropriate to its size and straw availability, as compared to the status quo of firing coal only. The lifetime of the bioenergy plant was assumed to be ten years and assessments were conducted before taxes.

[2] Prices are given in US dollars, assuming a currency conversion rate of 6.14 renminbi to 1 US dollar
[3] 10% transport and handling loss during straw collection

***Financial parameters***

Literature estimates of the capital costs of converting coal-fired power stations to cofiring capability vary from zero costs (where biomass is briquetted before cofiring; Liu *et al.*, 2014) to between \$59-426 $kW^{-1}$ installed biomass capacity[4] (US Dept. of Energy, 2000; Al-Mansour & Zuwala, 2010). The baseline assumption of this study is therefore the mid-point of this latter range (\$243$kW^{-1}$ installed biomass capacity), and this figure is tested in the sensitivity analysis.

Coal price is assumed to be \$97$Mg^{-1}$ and coal energy density is assumed to be 23,000 MJ $Mg^{-1}$ (Bloomberg, 2014). An average straw energy density is calculated individually for each powerstation according to the proportion of maize, wheat and rice straw that is available in the collection radii, and the energy densities of these straw types (see Table 3). Straw price is assumed to be \$47$Mg^{-1}$, calculated as a middle range estimate from recent publications regarding the production of bioenergy from agricultural residues in China (Zhang *et al.*, 2013, 2014; Liu *et al.*, 2014; Gosens, 2015).

Costs of straw transportation and pre-treatment were derived from a number of sources. According to Liu *et al.*, (2014) and Zhang *et al.*, (2013) straw is collected and briquetted by a 'middle-man' enterprise, which then sells briquettes to the power station. These pre-treatment costs are estimated at \$29 $Mg^{-1}$ plus a 10% profit for the straw briquette business of \$2.9 $Mg^{-1}$.

Straw transportation was assumed to be by road. Although the rail network is a major transport means for coal to China's powerstations, straw resources are low in energy density and far more dispersed at their source than coal. Therefore they are better accessible by road

[4] Inflation adjusted using (Forex, 2015).

than by rail. Straw transportation distance was determined for each powerstation using an equation from French, (1960) assuming a circular radius and square road grid:

$$D_i = \sqrt{\frac{S_i}{640 \cdot Y_i \cdot d_i}}$$

where $D_i$ is the average distance (miles) each Mg of straw feedstock is hauled for power station *i*; $S_i$ is the annual amount of feedstock required for power plant *i*, multiplied by 0.5 to reflect two growing seasons; $Y_i$ is the average biomass yield per acre in the 50km collection radius of power station *i*; $d_i$ is the fraction, or density, of land on which agricultural residues are produced within the 50km collection radius of each power station *i*; and 640 is a conversion factor for the number of acres per square mile. The mean calculated distance per Mg of straw was 86km, with a range of 24km to 168km.

Coal-fired power plants generate some revenue from sales of fly-ash to cement industries. Research has demonstrated that cofiring biomass with coal at up to 25% energy replacement ratios does not significantly affect fly-ash quality and is able to meet the Chinese standard (GB/ T1596-2005) for sale to the cement industries (Wang *et al.*, 2011b). However, cofiring biomass with coal may reduce the quantity of fly-ash produced per unit energy output, as biomass contains a lower proportion of ash per unit weight than coal (Al-Mansour & Zuwala, 2010). Therefore a conservative assumption was made that sales of fly-ash at each power plant would decrease linearly with the ratio of biomass-cofiring. I.e., a 3% rate of cofiring would lead to a 3% reduction in revenue from sales of fly-ash. Fly-ash is assumed to be sold at \$6.5Mg$^{-1}$ and it is assumed that, under standard operating conditions, 100 Mg coal would produce 3Mg fly-ash (expert opinion).

The grid-purchase price for electricity generated from coal varies according to the contracts agreed between power station owners and the Chinese government, which are based on powerstation age, efficiency and sulphur emissions. Expert opinion and available data

(Bloomberg, 2012; Gosens, 2015) suggest that the average price is around \$0.068kWh$^{-1}$, and under China's bioenergy subsidy scheme, this price increases to \$0.12kWh$^{-1}$ for bioenergy derived from agricultural residues (Zhang *et al.*, 2014).

## Results

### *Geographic co-location of China's agricultural residues and coal-fired power plants*

There is substantial co-location of straw energy (terajoules; TJ) and existing coal-fired power stations in China. Figure 2 provides a visual depiction of the distribution of China's straw resources, overlaid with the location of power plants, and their respective 50km straw collection radii.

*Figure 2: Geographic co-location of China's straw resources (TJ per $km^2$) and power plant collection radii (50km)*

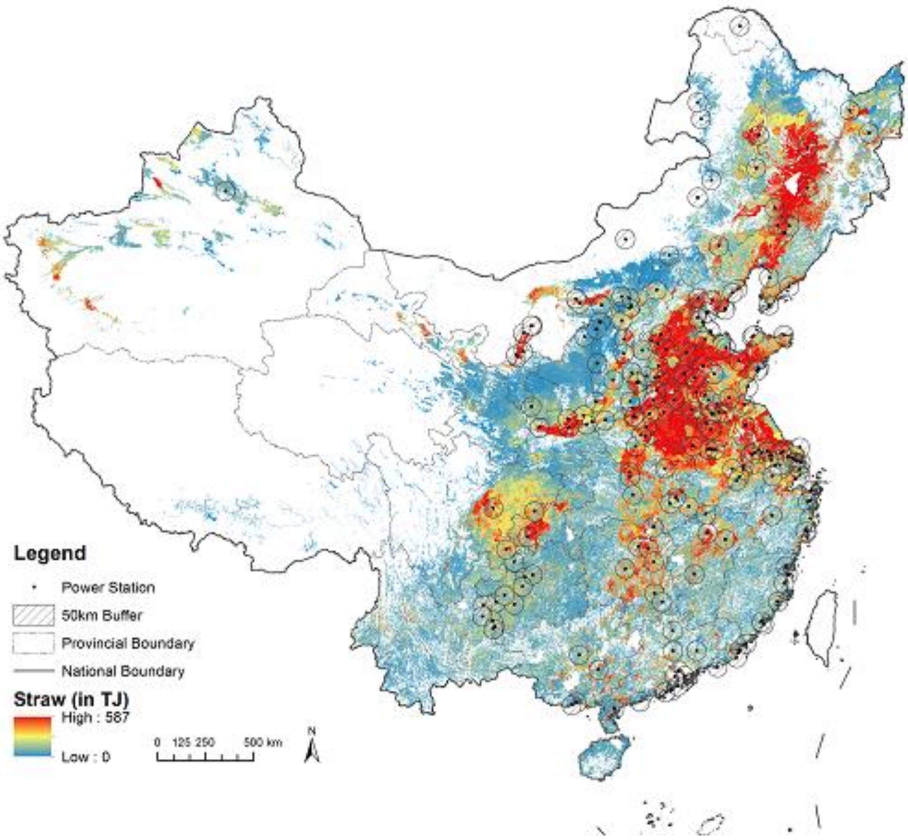



Table 4 outlines the energy (TJ) contained in the maize, wheat and rice straw resources that are located within 20km and 50km radii of the powerstations, and the proportion of China's total maize, wheat and rice straw resources that this accounts for. Our dataset estimates China's maize, wheat and rice straw resources at 6,100,000 TJ, which is broadly comparable to other estimates of 5,861,000 TJ (Jiang *et al.*, 2012) and 4,390,000 TJ (Wang *et al.*, 2013). Notably, 39% of China's straw resources are situated within 50km of the powerstations identified in the dataset.

*Table 4 – Straw availability (TJ and % of total) within 20km and 50km radii of powerstations*

| | Straw (TJ) | Of total (%) |
|---|---|---|
| 20km | 570,000 | 9 |
| 50km | 2,370,000 | 39 |

***Technical cofiring potential of power plants***

Table 5 outlines the number of powerstations that can cofire at a range of cofiring rates (1-10%) at 20km and 50km radii, and the estimated number of TWh that would be produced. We find that 68, 65, and 63% of powerstations can cofire at 1% or more using straw within a 20km radius for straw removal scenarios 1, 2 and 3 respectively, and that 82, 81 and 80% of powerstations can cofire at 1% or more within a 50km radius, for straw removal scenarios 1, 2 and 3 respectively. Interstingly, a significant proportion of powerstations can cofire at 10% (39, 31, and 24% for straw scenarios 1, 2 and 3 respectively) within a 50km straw collection radius. In fact, straw availability suggests that higher cofiring ratios would be possible for many of these powerstations, however an upper limit of 10% is placed on this analysis to account for the technical feasibility of cofiring relatively high-ash content feedstocks with coal.

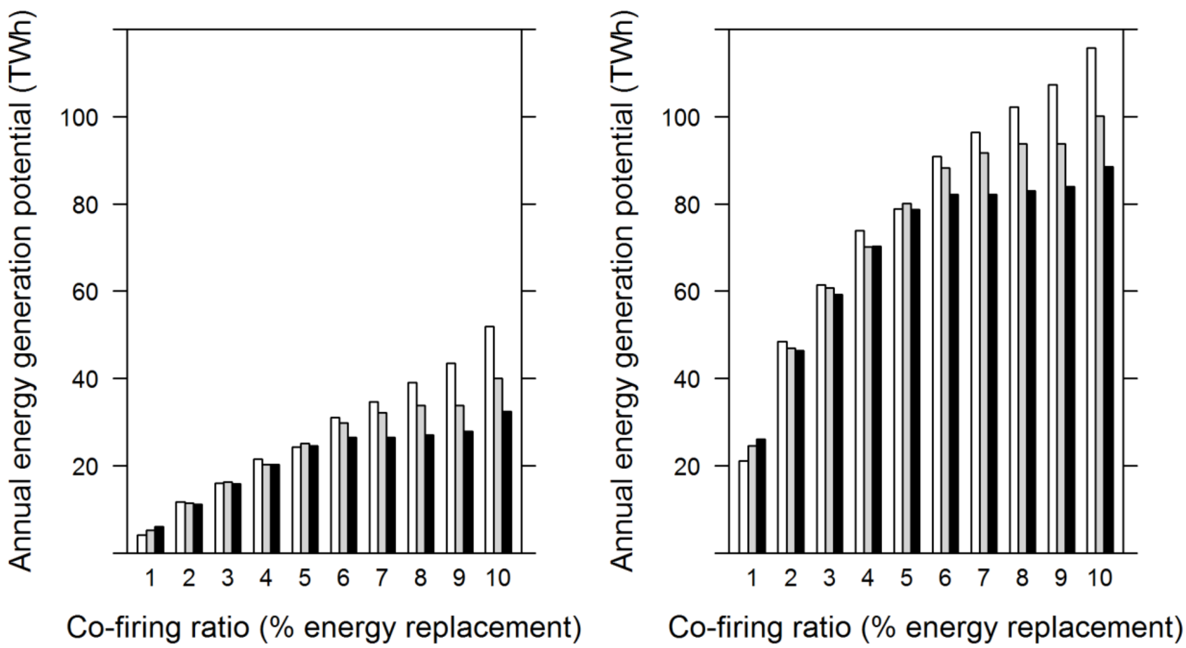
*Table 5 – Number of powerstations (n) that can co-fire at each ratio, and the subsequent bioenergy that this would produce (TWh) in each of the three straw collection scenarios*

| Radius | Straw Scenario | | 1% | 2% | 3% | 4% | 5% | 6% | 7% | 8% | 9% | 10% | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20km | 1 | n | 47 | 47 | 18 | 18 | 7 | 13 | 7 | 8 | 7 | 11 | 183 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | TWh | 4.2 | 7.5 | 4.3 | 5.5 | 2.7 | 6.9 | 3.6 | 4.4 | 4.4 | 8.4 | 51.9 |
| | 2 | n | 64 | 39 | 21 | 11 | 13 | 11 | 5 | 3 | 0 | 8 | 175 |
| | 2 | TWh | 5.3 | 6.2 | 4.8 | 4.0 | 4.9 | 4.7 | 2.4 | 1.6 | 0.0 | 6.3 | 40.1 |
| | 3 | n | 77 | 34 | 18 | 15 | 12 | 5 | 0 | 1 | 1 | 6 | 169 |
| | 3 | TWh | 6.1 | 5.1 | 4.7 | 4.5 | 4.2 | 2.0 | 0.0 | 0.6 | 0.8 | 4.5 | 32.5 |
| 50km | 1 | n | 20 | 19 | 18 | 14 | 18 | 8 | 6 | 7 | 6 | 104 | 220 |
| | 1 | TWh | 21.1 | 27.4 | 13.0 | 12.4 | 4.9 | 12.1 | 5.5 | 5.8 | 5.2 | 8.4 | 115.7 |
| | 2 | n | 29 | 23 | 23 | 14 | 8 | 13 | 8 | 9 | 6 | 83 | 216 |
| | 2 | TWh | 24.5 | 22.4 | 13.8 | 9.3 | 10.0 | 8.1 | 3.4 | 2.1 | 0.0 | 6.3 | 100.1 |
| | 3 | n | 31 | 30 | 23 | 15 | 10 | 11 | 10 | 9 | 11 | 63 | 213 |
| | 3 | TWh | 26.1 | 20.3 | 12.9 | 11.0 | 8.5 | 3.5 | 0.0 | 0.8 | 1.0 | 4.6 | 88.5 |

Combining this data into a cumulative analysis, Figure 3 demonstrates that, if all power plants were to co-fire their highest spatially and technically feasible straw:coal ratio, up to a maximum of 10%, China could produce an annual 52, 40, or 33TWh of bioenergy for straw scenarios 1, 2 and 3 within a 20km straw collection radius, or 116, 100, or 89TWh of bioenergy for straw scenarios 1, 2 and 3 within a 50km straw collection radius.

*Figure 3- Cumulative totals of annual bioenergy generation (TWh) from agricultural residue cofiring at 1-10% cofiring ratios, within 20km and 50km straw collection radii,and under different straw availability scenarios*



These numbers are very significant when compared to the current generation totals of other renewable energy technologies in China. For example, solar installations in China produced 8.7TWh in 2013, wind produced 141TWh, and nuclear contributed 112TWh. Moreover, these results suggest that cofiring straw could contribute significantly to China's 2020 target to install 30GW of bioenergy generation capacity, which is equivalent to a generating capacity of 148.8TWh per year (Xingang *et al.*, 2013). Within a 50km radius, the technical potential for cofiring is estimated at 78%, 67% and 60% of this target for straw removal scenarios 1, 2 and 3, respectively.

### *Economic feasibility of cofiring with and without subsidy support*

The internal rate of return (IRR) is calculated for all 220 powerstations that are able to co-fire at a biomass:coal energy replacement ratio of between 1 - 10%, within a straw collection radius of 50km. The TWh of bioenergy produced by all cofiring power plants with IRRs of 8% and over are summed together to estimate the bioenergy generation that would result under a variety of technical and financial scenarios.

Under baseline assumptions (see Table 6) and without the support of China's bioenergy feed-in-tariff, cofiring makes a significant loss at all power stations and zero TWh of bioenergy are produced.

*Table 6 – Parameter baseline, lower and upper values used for sensitivity analysis*

| Parameter | Baseline | Low | High | References |
|---|---|---|---|---|
| Capital cost ($ kW installed capacity$^{-1}$) | 243 | 59 | 426 | US Dept. of Energy, (2000); Al-Mansour & Zuwala, (2010) |
| Straw purchase (from farmer; $ Mg$^{-1}$) | 47 | 34 | 78 | Zhang *et al.*, (2013, 2014b); Liu *et al.*, (2014) |
| Straw pre-treatment[1] ($ Mg$^{-1}$) | 32 | 16 | 48 | Liu *et al.*, (2014) Zhang *et al.*, (2013) |

| | | | | |
|---|---|---|---|---|
| Straw transport[1] ($\$ Mg^{-1} km^{-1}$) | 0.49 | 0.24 | 0.73 | Liu *et al.*, (2014) |
| Coal purchase[1] (at power plant gate; $\$ Mg^{-1}$) | 97 | 48 | 145 | Bloomberg, (2014) |
| Coal energy density ($MJ Mg^{-1}$) | 23000 | 18700 | 29300 | Bloomberg, (2014); Liu et al., (2014) Liaoning Government, (2014); |
| Coal energy price ($\$ kWh^{-1}$) | 0.068 | 0.043 | 0.080 | Bloomberg, (2012); Gosens, (2015) |

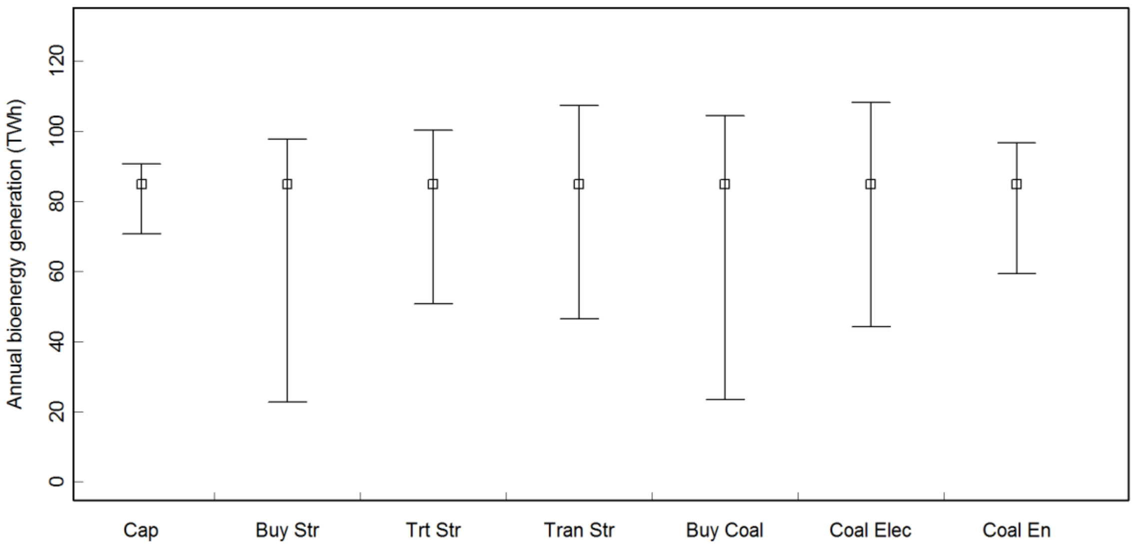
[1] In the absence of appropriate range data, a mid-range value is taken from the literature and varied by +/- 50%

In contrast, if the current bioenergy feed-in-tariff ($\$0.12 kWh^{-1}$) is used to value the bioenergy produced from agricultural residues at the coal-fired power stations, cofiring is profitable at 139, 126 and 114 powerstations across China, generating a cumulative total of 99.8, 84.9 and 71.8 TWh of bioenergy under straw scenarios 1, 2 and 3, respectively. This represents 48, 57 and 67% of China's expected bioenergy generation under the 30GW target.

Sensitivity analysis on key economic and energetic parameters using values from Table 6 demonstrates that the profitability of cofiring, and resultant anticipated TWh of bioenergy generation, is strongly influenced by a variety of parameters.

Figure 4 shows that the changes in the purchase prices of coal ('Buy Coal') and straw ('Buy Str') have the greatest impact on the profitability of, and related predicted energy generation from, cofiring agricultural residues at China's powerstations. The straw transportation ('Tran Str'), straw treatment price ('Str Trt') and the grid price for coal-fuelled electricity ('Coal Elec) are also important in determining cofiring profitability, whereas the energy content of coal ('Coal En') and the capital costs of retrofitting powerstations to accept straw biomass ('Cap') have a relatively small impact on the anticipated bioenergy generation as it relates to profitability. In the third, and most conservative, straw removal scenario, the upper limits of straw cost ($\$78 Mg^{-1}$) result in the estimate bioenergy production from cofiring dropping to just 15TWh. However, this still represents 10% of the bioenergy production that might be expected if China were to reach its 30GW target.

*Figure 4 - Variation in annual bioenergy generation (TWh) from cofiring according to sensitivity analysis using key economic and energetic parameters*



**Discussion**

Overall we find that there is significant spatio-techno-economic potential for China to generate sizeable quantities of bioenergy by cofiring available agricultural residues in its coal-fired power stations, if the government extends the current bioenergy feed-in-tariff to include low ratio biomass cofiring operations.

Under baseline economic conditions, and without subsidy support, cofiring agricultural residues is not profitable for powerstations. However, we predict that extending the subsidy to include cofiring could stimulate between 72-100 TWh of bioenergy generation, depending on the assumed removal rate of straw. This could account for between 47-68% of the bioenergy generation that is expected under China's 2020 target to install 30GW of bioenergy production capacity.

These results are subject to two caveats. Firstly, the profitability, and related bioenergy generation potential, of cofiring is highly sensitive to the purchase price of coal and straw. When varied independently, neither the highest straw price ($78 Mg^{-1}$) nor the lowest coal price ($48Mg^{-1}$) bring the estimated bioenergy generation to zero TWh, with a predicted output of 15.3TWh nad 15.9TWh, respectively, under the most conservative straw removal assumptions (scenario 3). Nevertheless, if the straw price were to rise and coal price were to simultaneously fall, this could seriously affect the profitability of cofiring agricultural residues. However, one benefit to cofiring in comparison to biomass-only generation units is that cofiring operations are better able to respond to such changes in market conditions. For example, when the straw price is too high, powerstations can focus on coal-fuelled electricity generation, and vice versa, without experiencing prolonged periods of reduced income. In contrast, biomass-only bioenergy projects are very vulnerable to changes in straw purchase price, and may suffer long periods of financial losses that can be hard to recover from. This may at least partly explain reports of bioenergy plant shut-downs across China in recent years (Han *et al.*, 2008; Zhao & Yan, 2012; Xingang *et al.*, 2013; Zhang *et al.*, 2013). Therefore the concerns over the sensitivity of these results to straw and coal purchase prices are important, but are arguably less significant in their impact on bioenergy generation from cofiring as compared to biomass-only bioenergy projects.

A second caveat is that China's 30GW target for installed bioenergy generating capacity is likely to be driven partly by a desire for additional electricity generating capacity, whereas cofiring works within existing installed capacity, directly replacing coal feedstock with biomass. Nevertheless, given the current challenges faced by biomass-only electricity generation units, it is possible that cofiring straw is a more efficient use of China's agricultural straw resources, and that total installed renewable capacity may more cost-effectively be expanded via solar, wind or hydro projects, rather than biomass-only units.

In conclusion, this analysis demonstrates that significant bioenergy can be generated by cofiring agricultural residues in China's existing coal-fired power stations, taking into account spatial, technological and economic opportunities and constraints. Given reports of the difficulties that biomass-only power generation units have encountered, and the relatively smaller investment costs, risks and vulnerability to biomass prices of cofiring compared to biomass-only operations, these results provide a convincing case for the Chinese government to extend their existing bioenergy feed-in-tariff to include cofiring operations at low biomass:coal ratios.

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